RANKING ENERGY INFLUENTIAL PARAMETERS – HOW BUILDING TYPE AFFECTS THE PARAMETERS' INFLUENCE

Rafaela Orenga Panizza[1], and Mazdak Nik-Bakht[1]
[1]Concordia University, Montreal, QC (Canada)

ABSTRACT

Building performance simulation is normally performed at early stages of design; when parameter related decisions are made, but changes can still be made without major impacts on the design scope. Ideally, energy simulations would be most beneficial when integrated within the decision-making of parameters, however, due to the large number of possible scenarios, that is not feasible. Other authors performed sensitivity analysis to evaluate the impact that parameters have on to the building's energy consumption; but most only analyzed a single model. This study is evaluating the dependency of sensitivity analysis results on the building type. Results show that the impact caused by most analyzed parameters is sensitive to building model. Based on this finding, future studies will be able to begin investigation of what characteristics cause such differences in behavior.

INTRODUCTION

With the growth in popularity of more energy efficient buildings, building energy modeling (BEM) has become a very important step in the building design process, mostly to ensure compliance with building energy codes. Energy simulations are performed by a simulation software, that takes the building model as its main input. This happens at an early stage of design, which is when important decisions can be made without major additional costs. Today, however, many design parameters are almost fixed by the time simulation stage begins. That happens because, when there is a large possibility of scenarios (combining different building parameter attributes), it becomes extremely time consuming and computationally expensive to simulate all scenarios; hence, making it infeasible during the design process. As a result, quantitative energy analyses are not being used as effectively in the decision making for building design.

Using BEM during the early decision-making, requires limiting the number of possible scenarios (decision alternatives) to only the most relevant ones (in terms of energy efficiency). As a step forward, this research is an attempt towards investigating the possibility of developing a "universal ranking" system for energy influential parameters in Québec, Canada. Such a system would be beneficial to help designers prioritize the parameters that more significantly influence energy consumption, therefore decreasing the number of scenarios to be analyzed through a simulation phase. Several previous works have studied the impact of building parameters on the energy performance of a building model. Investigated literature showed different case studies using a variety of simulation engines such as ESP-r (Lomas and Eppel 1992, Hopfe and Hensen 2011, Sanchez, et al. 2014, Tian 2013), TRNSYS (Sun 2015, Gagnon, Gosselin and Decker 2018, Rivalin, et al. 2018, Tian 2013), DOE-2 (Lam and Hui 1996, Ouertani and Krarti 2006, Ourghi, Al-Anzi and Krarti 2007, Tian 2013), EnergyPlus (Smith, et al. 2012, Nembrini, Samberger and Labelle 2014, Pushkar, Becker and Katz 2005, Attia, et al. 2012, Petersen, Kristensen and Knudsen 2019, Tian 2013, Delgarm, et al. 2018); and, in addition, a variety of sampling and sensitivity analysis methods to analyze the impact of the building parameters have been investigated.

RELATED WORKS

The investigated literature showed a variation between local and global methods for sensitivity analysis of parameters in the building energy modeling field. Local methods have shown the capability of ranking parameters based on their impact on the output with a relatively low computational cost (Tavares and Martins 2007, Pushkar, Becker and Katz 2005, Ourghi, Al-Anzi and Krarti 2007, Sun 2015) however, with a large number of parameters, this type of analysis becomes time-intensive (Martin Heine Kristensen 2016). Global sensitivity analysis methods, on the other hand, can provide very advanced results but always will require a very costly computation effort (Capozzoli, Mechri and Corrado 2009, D. Garcia Sancheza 2014, Mara and Tarantola 2008). The Morris Method, however, is an intermediate method due to its cooperation between quality of results and computational cost (D. Garcia Sancheza 2014) thanks to its one-parameter-at-a-time (OAT) sampling method (same as local methods).

The reviewed papers have investigated a pool of different cases such as single-zoned rooms to office buildings, townhouses, residential buildings, etc. as well as generic buildings (Lomas and Eppel 1992, Lam and Hui 1996, Pushkar, Becker and Katz 2005). All of these case studies were modeled in different locations (represented by the weather files used for simulation) such as Hong Kong (Lam and Hui 1996), Portugal (Tavares and Martins 2007) and Denmark (Dreau and Heiselberg 2014, Heiselberg, et al. 2009). These studies that test sensitivity of building performance to the input parameters have shown a large range of tested variables. It was noticed that variables related to envelope insulation, window sizes, and mechanical systems were chosen to be investigated in the majority of the analyzed literature, and they showed to be parameters of great importance in the building energy field.

Regardless of the method used, the reviewed literature reports success in analyzing the energy influential parameters of their case studies. However, all of these studies only analyze one building model, which makes their results "case-dependent". To overcome that gap, and move forward towards the investigation of the feasibility of developing a "universal ranking" system for building parameters in cold climate (Québec, Canada), the objective of this paper is to evaluate the dependency of sensitivity analysis results on the building type being analyzed.

The remaining of this paper is organized as follows. First, an overview of the analyzed cases will be shown. Followed by the methodology used from the selection of parameters and their input ranges to output generation. Next, the methods used for analyzing the outputs. Then, the results and discussion of the analyzed results. And finally, the summarized findings and their limitations are pointed out, along with the next steps for advancing this study.

STUDIED CASES

The U. S. Department of Energy (DOE) and three of its national laboratories, in collaboration with the ANSI/ ASHRAE/ IES Standard 90.1, have developed a set of commercial reference building models. These 17 models represent about 80% of the commercial and high-rise residential floor area in the United States (U. S. Department of Energy 2018). In order to cover a wide range of building types (excluding single-family houses), this paper uses all 17 reference building models. In this pool of models there are 11 low-rise and 6 high-rise buildings. The ANSI/ASHRAE/IES Standard 90.1 divides buildings into low- and high-rise based on their number of stories, buildings with 3 stories or less are considered low-rise (Barlett, Halverson and Shankle 2003). Details of the investigated models can be found in Table 1 .

Table 1 Model descriptions

REFERENCE BUILDING	NUMBER OF FLOORS	FLOOR AREA (FT^2)	RISE
Full Service Restaurant	1	5,500	Low-rise
High-Rise Apartment	10	84,352	High-rise
Hospital	5	241,351	High-rise
Large Hotel	6	122,120	High-rise
Large Office	12	498,588	High-rise
Medium Office	3	53,628	Low-rise
Mid-Rise Apartment	4	33,740	High-rise
Outpatient	3	40,946	Low-rise
Primary School	1	73,960	Low-rise
Quick Service Restaurant	1	2,500	Low-rise
Retail Stand-alone	1	24,962	Low-rise
Retail Strip Mall	1	22,500	Low-rise
Secondary School	2	210,887	Low-rise
Small Hotel	4	43,200	High-rise
Small Office	1	5,500	Low-rise
Supermarket	1	45,000	Low-rise
Warehouse	1	52,045	Low-rise

METHODOLOGY

This study focuses on parameters that influence energy performance in different building models with different sizes. With that in mind, the selected output variable for the analyses in this paper is energy use intensity (EUI - kBtu/ft^2-yr). The aim was to vary the studied parameters in all models to be able to compare their effect onto the selected output. The simulation tool used to manipulate the models (by varying the parameters being studied) and generate outputs for this study was OpenStudio (NREL, OpenStudio n.d.), which is an open-source software application that uses EnergyPlus and advanced daylight analysis using Radiance. The investigated variation of parameters was automated with the help of OpenStudio measures, which are programs capable of accessing and changing OpenStudio models.

Parameters Investigated

The initial set of parameters being investigated in this paper were suggested by our industry partner, a Québec-based energy consultant, based on their consulting experience in the field of building energy analysis. Some of the selected parameters are of continuous nature and some are of discrete nature.

Those parameters cover aspects such as window to wall ratio (W/W) for south (S), north (N), east (E) and west (W) facades; wall and roof insulation (R-value); window glazing type (WT) Table 3; lighting system type (1: troffer; 2: high-bay/low-bay) and efficiency (LE); and heating, ventilation and air conditioning (HVAC) system type Table 2. Window glazing, HVAC and lighting system type are discrete parameters.

Table 2 Investigated discrete values

PARAMETER	UNIT	DISCRETE VALUES
Window-to-Wall Ratio (W/W)	n/a (ratio)	0, 0.2, 0.4, 0.6, 0.8
Roof R Value	Ft^2h^2/Btu	29.294, 39.018, 48.112, 57.206, 66.3
Wall R Value	Ft^2h^2/Btu	29.294, 39.018, 48.112, 57.206, 66.3
Window Glazing Type (WT)	n/a (type)	1, 2, 3, 4, 5, 6, 7, 8, 9 (Table 3)
HVAC Type	n/a (type)	1, 2, 3, 4, 5, 6, 7, 8 (Table 4)
Lighting Efficiency (LE)	% reduction	45.3
Lighting Type	n/a (type)	1, 2

For each of the above-mentioned continuous parameters, a uniform distribution was defined by 5 discrete input values that were selected based on the appropriate ranges to be tested. Lighting system efficiency, as an exception, only takes the maximum system efficiency as an input since its impact onto the output is linear. These ranges were based on the minimum requirements for ASHRAE 90.1 2007 and past reports from the industry partner. For the above-mentioned discrete parameters, uniform distributions on discrete values were defined for window glazing and HVAC types. The chosen types were selected with the help of the industry partner while trying to cover the most used types in the Québec building industry. Chosen values for the parameters with continuous nature can be found in Table 2. All tested parameters are analyzed at an OAT basis (where parameters are evaluated in turn) since there are no co-dependencies between them. This study, however, does not consider the compound effect of co-variation of multiple parameters.

Table 3 Window glazing types

#	GLAZING	THICKNESS (GLAZING/ FILLING)	GAS FILLING
1		3mm/6mm	Air
2	Double Clear	6mm/13mm	
3			Argon
4		3mm/6mm	Air
5	Double Grey	6mm/13mm	
6			Argon
7		3mm/6mm	Air
8	Triple Clear	3mm/13mm	
9			Argon

Model Preparation

The original DOE models, as acquired, only contained geometric data of the building and their zone breakdown. To prepare the models for simulation, new baseline details were required: appropriate construction and schedule sets; appropriate occupant definition, lights, and electric equipment definitions; assignment of loads to their respective space types; and the appropriate cooling and heating thermostat schedules.

Table 4 HVAC types (Building Component Library (BCL) n.d.)

#	TYPE
1	AEDG K12Dual Duct DOAS
2	AEDG K12 HVAC Fan Coil DOAS
3	AEDG K12 HVAC GSHP DOAS
4	AEDG Office HVAC ASHP DOAS
5	AEDG Office HVAC Fan Coil DOAS
6	AEDG Office HVAC VAV Chilled Water
7	AEDG Office HVAC VAV DX Coil
8	AEDG Office HVAC WSHP DOAS

Following the baseline setup for all models, they had to be prepared for the sensitivity analysis simulations. The remaining step to preparing the building models was to load all window glazing types to the model library (to be tested throughout the analysis).

In order to keep consistency among the analyses, the baseline models were set, before the simulation, to the same HVAC type (ASHRAE 90.1-2007 Sys 7 Baseline Measure); R-values for roof and walls (20.83 and 15.625 respectively); lighting system type (surface ambient); and window glazing type, which the models, as acquired, already had.

Significance of Parameters' Impact

To test the impact significance of each analyzed parameter, the t-test was selected. This test is only applicable when the sample or population follow a normal distribution. The t-tests were performed in three different variants. All tests analyzed parameters separately but the samples were different: the first test used the entire dataset (17 ASHRAE models), the second used only the low-rise buildings (11 models), and the last one only used the high-rise buildings (5 models). Due to their small sizes, the distribution behavior of each parameter throughout all models could not be properly investigated.

The method used to perform the t-test was a single sample upper-tailed test, where the null hypothesis is $H_o \leq x$ and the alternative hypothesis is $H_a > x$. In this study, 'x' is the necessary increase in EUI that a parameter needs to cause in order to be considered to have a significant impact. Based on (Beguery, et al. 2015), the necessary energy increase to consider a parameter to have impact is 3%. We took the same value as the threshold of significance for the difference among cases' outputs. The null hypothesis must be rejected in order to say that the parameter has a statistically significant impact on the output, and the parameters that appear to be insignificant in all three tests must be disconsidered for the remainder of this paper's analysis.

Classification of Parameters

The remaining parameters were then ranked based on the range existing between their minimum and maximum values (percentage increase from minimum to maximum). Their normalized ranges for each models allowed for the development of a graph that mimics a continuous distribution graph (based on parameter ranking and their normalized impact). With this graph, the proper and proportional classification between 4 different levels of impact was then possible by using the Extended Swanson-Megill discretization method, which weights the 10th, 50th, and 90th percentiles of the continuous density function. The different levels of impact were: 'high' impact (parameters found to be above 0.9 percentile); 'medium-high' impact (parameters in between 0.5 and 0.9 percentiles); 'medium-low' impact (parameters in between 0.1 and 0.5 percentiles); and 'low impact' (parameters encountered below 0.1 percentile).

RESULTS AND DISCUSSION

When going through the above mentioned methodology, the analysis of the parameters makes it possible to find the parameters that have a significant impact on the energy use intensity of the models. Parameters with high significance are then kept for the remaining of the study, and will be used to investigate whether their significance would be sensitive to the case study model.

Significance of Parameter Impact

Table 5 shows the results of all three t-tests performed. As seen in the table, all three tests show that wall insulation and lighting system type does not have a statistically significant impact on the energy performance. The fact that they are not significant in all three samples shows that these parameters are not sensitive to the model being investigated and, for that reason, those two parameters were chosen to be ignored for the remainder of this analysis.

Table 5 Results for significance tests (Yes: significant impact; No: impact is nonsignificant)

PARAMETER	ALL MODELS	LOW-RISE	HIGH-RISE
Roof R-value	Yes	Yes	No
Wall R-value	No	No	No
W/W - S	Yes	Yes	Yes
W/W - N	Yes	Yes	Yes
W/W - E	Yes	Yes	Yes
W/W - W	Yes	Yes	Yes
WT	Yes	Yes	No
Lighting Type	No	No	No
LE	Yes	Yes	No
HVAC	Yes	Yes	Yes

When comparing the low-rise and high-rise population of models, it is noted that, while low-rise buildings only have two insignificant parameters, the high-rise results show an additional three parameters to the list of insignificance (roof insulation, window glazing type and lighting system efficiency). This difference suggests that the impact of different parameters does depend on the models being analyzed, and these results show that the height of the buildings is one of the parameters responsible for that change.

Classification of Parameters

Since the results of parameters' significance impact show a difference in the results for low- and high-rise buildings, the classification of parameters was carried-out separately. After classifying all the remaining parameters based on their impact level, it was noted that, for both low- and high-rise portions, the HVAC type is the only parameter in the high impact class 100% of the time (Figure 1 and Figure 2). The fact that the HVAC attribute does not vary between classes leads to the conclusion that this parameter's impact is not sensitive to the investigated model. For that reason, the remainder of this analysis will exclude the HVAC type parameter.

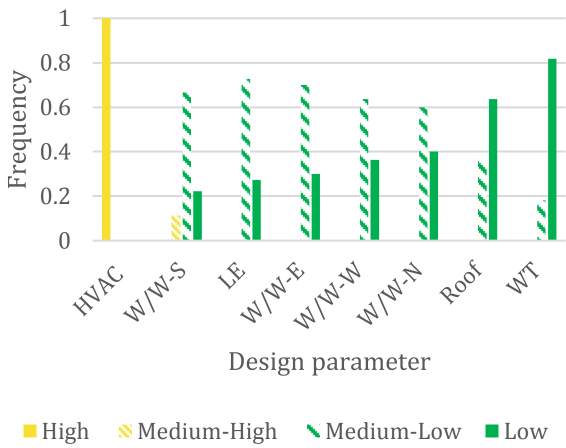

Figure 1 Low-rise frequency distribution

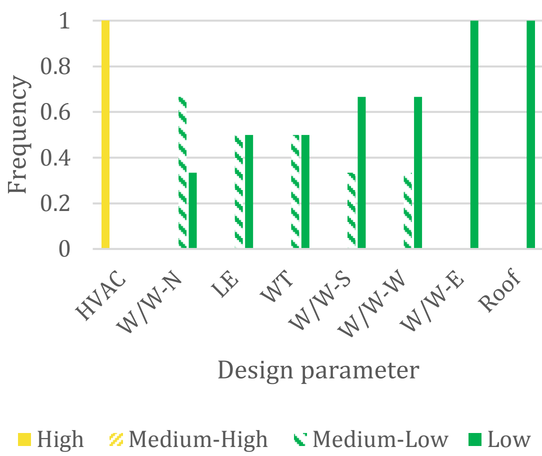

Figure 2 High-rise frequency distribution

To properly classify the remaining parameters, the same ranking and classification procedures were redone but without considering HVAC. The new frequency distribution graphs can be seen in Figure 3 and Figure 4. The low-rise graph (Figure 3) shows that most parameters are highly sensitive to the models, they vary between all four impact groups. The other two parameters (W/W-E and window type) vary between three of the four impact groups, which also shows that they are sensitive to the model. The above high-rise graph (Figure 4), on the other hand, only has W/W-N parameter being super sensitive (varying between all four different groups). High-rise also has four parameters (lighting system efficiency, W/W-S, W/W-W) varying between three impact groups, which are also sensitive; and the remaining two attributes (W/W-E and roof insulation) that do not show great sensitivity to the studied case, varying only between two levels.

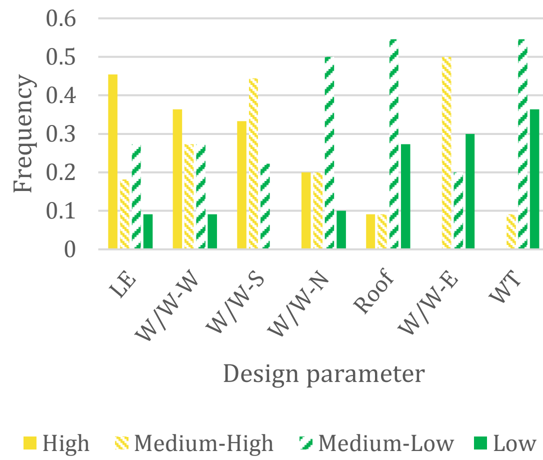

Figure 3 Low-rise frequency distribution without HVAC type

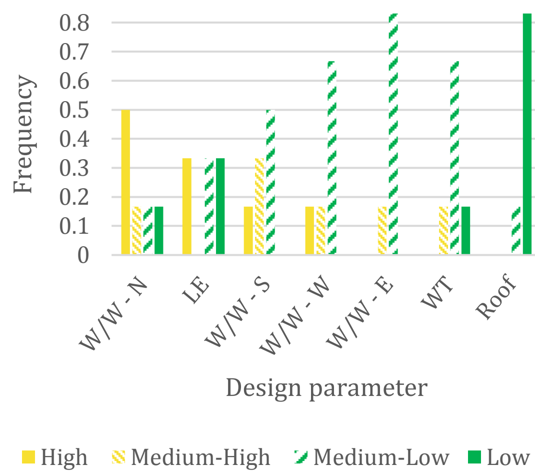

Figure 4 High-rise frequency distribution without HVAC type

The parameters in the above graphs were ordered based on their level of impact (from left to right: higher to lower impact). When comparing the low- and high-rise results, two main differences can be observed: the sensitivity of each parameter to the models (represented by their frequency in each impact class), and the order of parameters from higher to lower impact. These differences prove that the sensitivity analysis results do depend on the building type being analyzed.

CONCLUSION

With the goal to evaluate the dependency of energy influential parameters' impact on to the building type and attributes; this study tested the sensitivity of the building's energy performance to a set of parameters in all 17 ASHRAE baseline models. The outputs of all simulations, with the variation of one parameter at a time, were then analyzed for their statistical significance of impact. The test for significance showed a different set of nonsignificant parameters for low- and high-rise buildings. The overall test, as well as both low- and high-rise groups, however, showed that the lighting system type and wall insulation parameters were nonsignificant. The following step to the analysis classified the remaining parameters based on level of their impact onto the EUI. This analysis showed that the HVAC system type parameter has a large impact on the energy performance in all building models, which means that this parameter's sensitivity is not sensitive to the analyzed case, and therefore was taken out of the next steps of this study. The classification of the remaining attributes showed that most parameters are highly sensitive to the model in the low-rise group, and that, even though less sensitive, most parameters are still sensitive in the high-rise group as well.

Limitations of this study include the assumption that the investigated samples had a normal distribution behavior in order to test the parameters' significance of impact. The samples also had a difference in size (high-rise group being a lot smaller than low-rise). Another shortcoming of this study was the fact that the significance of impact levels were discretized (low, mid-low, mid-high and high), which limits the evaluation of sensitivity to the case study.

Even though this study presents a set of limitations, both, the difference in the results of the two groups and the frequency in which the parameters can be found in the different impact levels allow for the conclusion that the impact of energy influential parameters to the EUI does depend on the analyzed building model. Based on the drawn conclusion, the next steps to follow this study involve the use of a greater sample of building models, the investigation of the appropriate sample distribution for testing significance of impact,and investigation of other building parameters that may cause the different parameter behaviors as well the compound effect of varying more than one parameter at a time.

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